

Images and Spectral Performance of WFC3 Interference Filters

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ABSTRACT

The Wide Field Camera 3 (WFC3) is a panchromatic imager that will be deployed in the Hubble Space Telescope (HST). The mission of the WFC3 is to enhance HST's imaging capability in the ultraviolet, visible and near-infrared spectral regions. Together with a wavelength coverage spanning 2000 Å to 1.7 μm, the WFC3 high sensitivity, high spatial resolution, and large field-of-view provide the astronomer with an unprecedented set of tools for exploring all types of exciting astrophysical terrain and for addressing many key questions in astronomy today. The filter complement, which includes broad, medium, and narrow band filters, naturally reflects the diversity of astronomical programs to be targeted with WFC3. The WFC3 holds 61 UVIS filters elements, 14 IR filters, and 3 dispersive elements. During ground testing, the majority of the UVIS filters were found to exhibit excellent performance consistent with or exceeding expectations; however, a subset of filters showed considerable ghost images; some with relative intensity as high as 10-15%. Replacement filters with band-defining coatings that substantially reduce these ghost images were designed and procured. A state-of-the-art characterization setup was developed to measure the intensity of ghost images, focal shift, wedge direction, transmitted uniformity and surface feature of filters that could effect uniform flat field images. We will report on this new filter characterization methods, as well as the spectral performance measurements of the in-band transmittance and blocking.

Keywords: Keywords: Visible/UV, infrared, interference filters, transmittance, transmitted wavefront error

1. INTRODUCTION

The Wide Field Camera 3 instrument (WFC3) is a panchromatic camera that is being built by an Integrated Product Team (IPT) consisting of the Goddard Space Flight Center (GSFC), The Space Telescope Science Institute, Jet Propulsion Laboratory (JPL) and industry. Scientific guidance and input to the WFC3 project comes from a Scientific Oversight Committee (SOC) composed of members from the astronomy community, whom will be eventual users of this facility. Scheduled to be installed during Hubble Space Telescope (HST) fourth servicing mission, this camera will be a replacement for the Wide Field/Planetary camera 2 currently installed on the HST telescope. The WFC3 instrument is expected to enhance the capability of HST by incorporating two channels: the ultraviolet and visible channel (UVIS) with a spectral range of 200–1100 nm and infrared (IR) channel with a spectral coverage of 800–1700 nm.

The UVIS and IR filter specifications that will go along these channels were derived closely through interactions with the WFC3 SOC members and based on statistics of previous filter usage in other HST instruments. The filters as a group were designed to fully cover the UVIS and IR ranges sampling these wavelength regions with a mix of super-wide, wide, medium, and narrow bandwidths. A more detailed presentation of the impact these will have on the scientific goals for these filters will be discussed elsewhere.³ Some examples of the scientific investigations that will be enabled by these filters include emission and absorption line studies of a large

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variety of targets, not only stars but protostars/planetary disks, planetary nebulae, supernova remnants, and the interstellar medium. Also studies of faint galaxies, studies of newly formed stars, meteorological studies of planets, and observation of water and methane lines. Additional filters will be used as reference for the grisms and as continuum for other filters.

An original set of filters have already been fabricated, tested and selected for flight. However, a number of them, specially in the UVIS channel,² were found to exhibit ghost image intensities as high as 10–15%. The problem was traced to a filter design that consisted of cementing two or more substrates pieces, forming an air-gap (two substrates joined via small spacers) or multi-substrate (substrates bonded together with a layer of optical adhesive in between). A delay in the scheduled HST servicing mission gave enough time to procure a replacement for the filters with the worse ghost effects.

Similarly and although the characterization of the IR channel filters done at GSFC¹ did not show any evidence of ghosting, a few of the filters that were made on a fused silica substrate were also ordered for a replacement using a different substrate called IR80 glass. This substrate, unlike fused silica, does not transmit any light for visible wavelengths, and hence it provides a natural blocking for wavelengths shorter than 700 nm. This was necessitated due to an unexpected high quantum efficiency of newly developed IR CCD sensors down to the visible wavelengths of 500 nm.

Hence, the purpose of this paper is to present characterization work done on these remake filters. A state-of-the-art setup was built at GSFC to ensure that the new filters will exhibit minimal ghost images in addition to insure that they will meet the required spectral performance, focus shift, transmitted wavefront, and filter wedge.

The paper is organized as follows. First, we present the filter specification summary. Next, we will present a description of the experimental method used in collecting the optical data. This will be followed by a description of the phase retrieval procedure used to obtain the wavefront error and wedge information.

2. FILTER SPECIFICATION SUMMARY

The specifications for the manufacture of the UVIS and IR filters were based on scientific and optical design requirements. The JPL document # 18189 contains the detailed specifications for all the filters installed in WFC3. The central wavelength and passband had been recommended by the SOC. These were based on requirements for astronomical observations. Additional specifications were developed to assure that the quality of the spectral features being observed was maintained. This included specification such as out-of-band rejections, wavelength tolerance, and ripple within the passband, transmitted wavefront, and confocality between different filters.

Additional constraints came from the optical design of the instrument. A wavefront error budget was developed for the whole instrument; error budget numbers were developed for all of the optical components (including filters). These budget numbers determined specifications such as the transmitted wavefront and wedge tolerance. The optical design also played a role in the size of the filters. The filters had to be large enough to encompass clear a aperture for all field points on the detector.

In band transmission of greater than ninety percent was considered feasible based on discussions with manufacturers and with discussions with other users of filters within this wavelength region. A minimum peak transmission of 89 percent was chosen with a goal of 95 percent for narrow band and 98 percent for wide band filters. Also, the filters were specified with minimum ripples within its transmission band. We specified that the modulation within the spectral transmittance above and below the smooth curve could not fall below ninety percent of the peak transmission.

The actual definition of the spectral boundaries for the filters differed depending on the relative width of the filters. Wide and medium width filters were specified so that their passband were defined by their 50% transmission points. Narrow band filters were specified so that their 90 % peak transmission point defined the ends of the pass band. Narrow band filters also included wavelengths on the short and long end of the passband of which define the boundary where the transmission needs to be below one percent absolute. The manufacturer is free to design the narrow band filter that meet the criteria set by the 90 % peak and 1 percent absolute points. These specifications are necessary so that the narrow bands can be used for studying emission lines of interest and avoid nearby contaminating lines.

An out-of-band rejection level of 1×10^{-5} and 1×10^{-4} was specified for narrow band filters and wide band filters respectively. The rejection levels were specified to extend from either side of the passband to the detector cut-off.

In specifying filter thickness, it was required that there was not focus change for different filters (confocality). The manufacturer was free to choose substrates of which to make each filter. Different substrates will have different indices of refraction and would contribute differently to the total optical thickness. The thickness of each filter was therefore specified as equivalent to the optical thickness of 4 mm of fused silica at a wavelength of $1 \mu\text{m}$.

2.1. Transmitted Wavefront Error

The transmitted wavefront requirement flowed from the overall error budgeting of the instrument. It was chosen to be 0.02 waves RMS over any beam footprint at a wavelength of 633 nm. Previous work in measuring the transmitted wavefront of passband filters has shown that the application of passband coatings changes the optical figure of filters in a very predictable way. When multilayer coatings are applied to glass substrates, stress from the coating distorts the substrate. When analyzed in an interferometer the distortion takes the form of curvature with long radii of curvatures. This curvature can also be measured by reflective interferometry of the completed filter surfaces. Therefore, the specification required verification of the transmitted wavefront of the uncoated substrate and measurement of the optical figure of the final coated filter by reflective interferometry.

2.2. Wedge Tolerance

Wedge tolerance was specified for the completed filters to be 10 arc-seconds. Some astronomical investigations would be sensitive to the relative motion of images taken through multiple filters. Large wedges and variation of wedges between different filter types would cause variation of image position as filters were changed. A requirement was placed that the centroid of images as viewed through different filters be within a half of an 18 micron pixel. Analyses of this requirement, for the optical system led to the 10 arc-second wedge tolerance specification.

2.3. Environmental Test

Environmental specifications were placed on the infrared filters. A durable coating was specified that would be resistant to abrasion. Resistance to temperature excursions, humidity, and vibrations consistent with a launch environment were also imposed. The operational environment for the filters is aboard the Hubble Space Telescope where it will be exposed to vacuum and operated at 243 K. Significant time will pass before the instrument's final deployment and the environmental requirements were chosen such that the filter quality does not degrade upon exposure to various temperature, humidity and vibration conditions.

3. FILTER MANUFACTURING

Each filter discussed here was designed and manufactured on a single monolithic substrate. The substrates were polished by means of a double-sided polishing technique. This technique had been used successfully in the past to produce substrates with tight wedge tolerances and good transmitted wavefront. The final polished thickness was based on measured index of refraction data discussed later. BAT interferometry was done to assure that the substrate's transmitted wavefront was within specification. BAT interferometry also enabled rejection of samples of the substrate that exhibited sharp discontinuity in its index of refraction.

Reactive ion-assisted deposition was the chosen technique for the coating. The coating deposition material usually consisted of Niobium or Tantalum oxide. This coating method produces thin films of high density, the coatings are considered 'hard' because they are resistance to scratches and adhere tightly to the substrate surface. Typically, the blocker coating was placed on one side of the substrate while the band-defining coatings were placed on the opposing side. Design curves, showing passband and rejection, for all specified filters types were made and compared with the specifications. These curves were also reviewed by the science IPT members.

Prior to coating, the glass for the UVIS filters was pre-sized to 57.3mm on a side. The clear aperture and coated clear aperture are 53.238mm and 55.27mm respectively. On the other hand the IR filter substrate filters

are all one-inch disks. Several pieces were coated in the chamber at once. At least one piece was used as a witness for testing coating adhesion. Witness pieces were also used for environmental testing (temperature and humidity).

All coated pieces underwent several tests prior to shipping. Transmission passband testing was performed on all pieces. Transmission testing to verify out-of-band rejection was performed. Figure testing of each coated surface was also made. Prior to shipping, each filter was labeled and inspected. This inspection tested for scratch-dig specification and dimensional checks were also made. All of the out going tests and inspections were included in a data package. The transmission data was provided digitally as well as plotted.

4. EXPERIMENTAL DETAILS

4.1. Spectral Testing

The instrument used for measuring spectral transmittance is a grating spectrophotometer made by Perkin Elmer (model PE Lambda 950). This is a double-beam monochromator, ratio recording spectrometer that has a wavelength coverage of 185–3300 nm. The light sources are a tungsten-halogen lamp for the NIR and VIS ranges, and a deuterium (D₂) lamp for the UV region. The detectors consist of a photomultiplier tube (PMT) for the UV-VIS and a Pielter Cooled PbS detector for the NIR coverage. The maximum spectral resolution is 0.05 nm in the VIS/UV and 0.2 nm in the NIR region. The beam in the sample compartment has a rectangular shape whose height is 4 mm and the width varies according with resolution but it is typically between 1–2 mm wide. The instrument photometric response allows measurements of optical density (OD) up to 8 absorbance levels (with attenuated reference). The wavelength and photometric calibration is done after instrument power up by following a computer-controlled self-calibration routine that uses NIST traceable standards. The UV/VIS filters are tested at ambient temperatures (20 °C ± 2.5 °C), whereas the infrared (IR) filters are required to be measured at -30 °C (±1°C). The latter was possible by mounting the sample inside an Oxford cryostat fitted with appropriate windows for optical access in the spectral range of interest and sitting in the spectrometer sample compartment. The normalized filter transmittance T_{filter} is obtained according to the formula:

$$T_{filter}(\omega) = \frac{S_{filter} - 0\%_{Baseline}}{100\%_{Baseline} - 0\%_{Baseline}}, \quad (1)$$

where S_{filter} represents sample spectral transmission, at a normal angle of incidence, relative to the the filter transmission that includes the instrument response, $100\%_{Baseline}$ is the transmission without the sample, whereas $0\%_{Baseline}$ is the dark detector response obtained with the sample beam completely blocked. The uniformity of filter response was determined by sampling the transmittance over the filter area on a 5×5 grid pattern of points 10 mm apart in the vertical and horizontal directions. A motorized and computer-controlled x-y stage provided repeatable motion of the filter at these 25 positions. The uniformity in the out-of-band filter response was checked at the filter center and the four corners. The uniformity of the IR filters was verified by looking at the transmittance near the center and at four additional positions in a cross pattern (top, bottom, left, and right).

4.2. Imaging - FilterGEIST (Filter Ghost Evaluation Imaging Station)

Image testing of WFC3 UVIS replacement filters was performed with a dedicated optical setup called FilterGEIST (Filter Ghost Evaluation Imaging Station). So called because its original purpose was to reproduce and characterize ghost images seen in WFC3 testing, the setup has proven useful for characterizing other aspects of the filters that can be determined through imaging, including transmitted wavefront error (WFE), focal shift, and wedge. FilterGEIST is a single point imaging system using two off-axis parabolic mirrors as shown in Fig 1. An appropriate aperture stop is placed in the converging beam for an f/# of 31 to match the WFC3 UVIS channel beam. The filter itself is mounted on a 4-axis motorized assembly. This includes two translation stages to move the filter in X and Y, and two rotary stages to allow rotations of the filter around X and Y (tip/tilt). The filter can thus be moved so that the beam passes through any position on the filter at any desired angle. The CCD camera is a SBIG ST-6 with 23x27 μ m pixels and is mounted on a motorized stage for focus. This camera has the greatly beneficial feature of good sensitivity over the entire range of our tests, down to 200 nm and shorter.

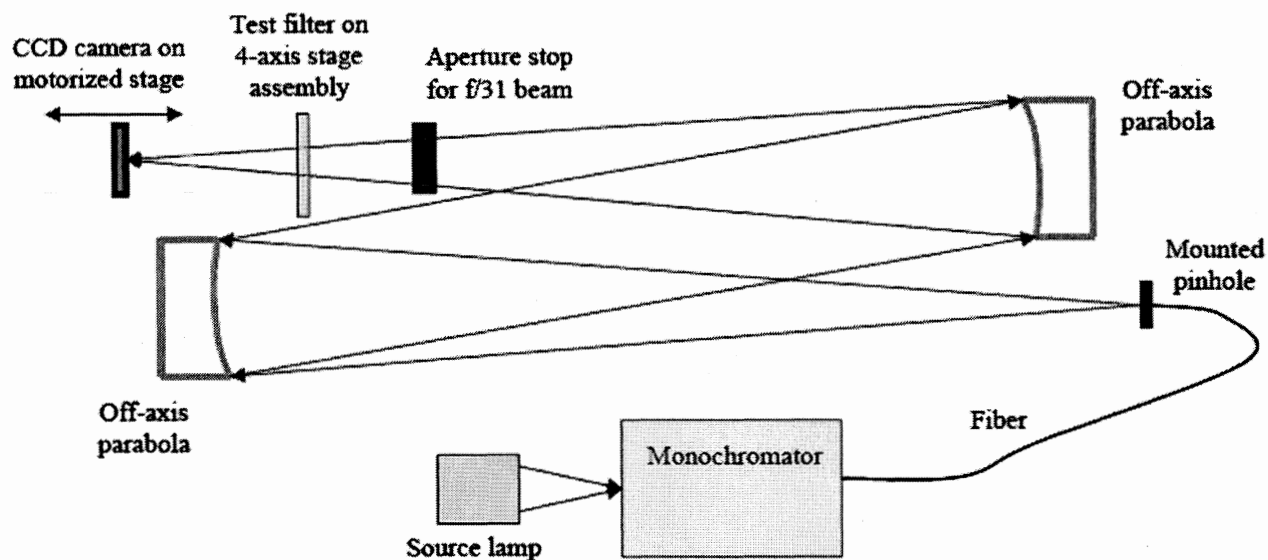


Figure 1. Filter Geist set up for wavefront measurements.

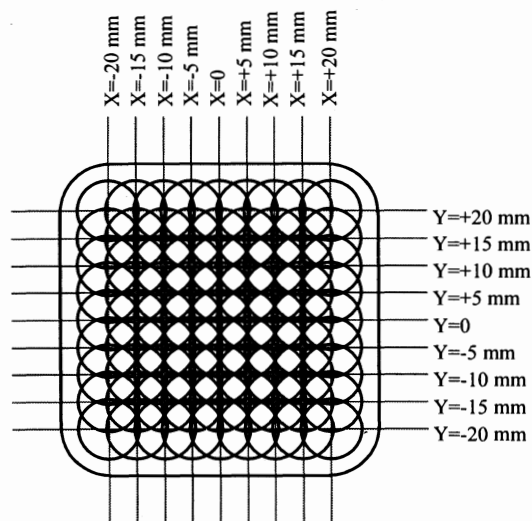


Figure 2. Array of translation positions for phase retrieval covering the filter. The beam footprint at each position is 11 mm.

4.2.1. Phase Retrieval

We acquire phase retrieval data in monochromatic light at the central wavelength of the filter through a 9x9 array of positions spaced by 5 mm as shown in Fig 2. For each position on the filter, images are taken at four different camera focus positions alternately with and without the filter. For wavelengths shorter than 400 nm, we use focus positions of ± 10 and ± 25 mm. For wavelengths longer than 400 nm, we use focus positions of ± 15 and ± 40 mm. All images are analyzed with customized PSF fitting software to extract wavefront phase information in the form of coefficients for the first 28 CODE V Zernike polynomials.

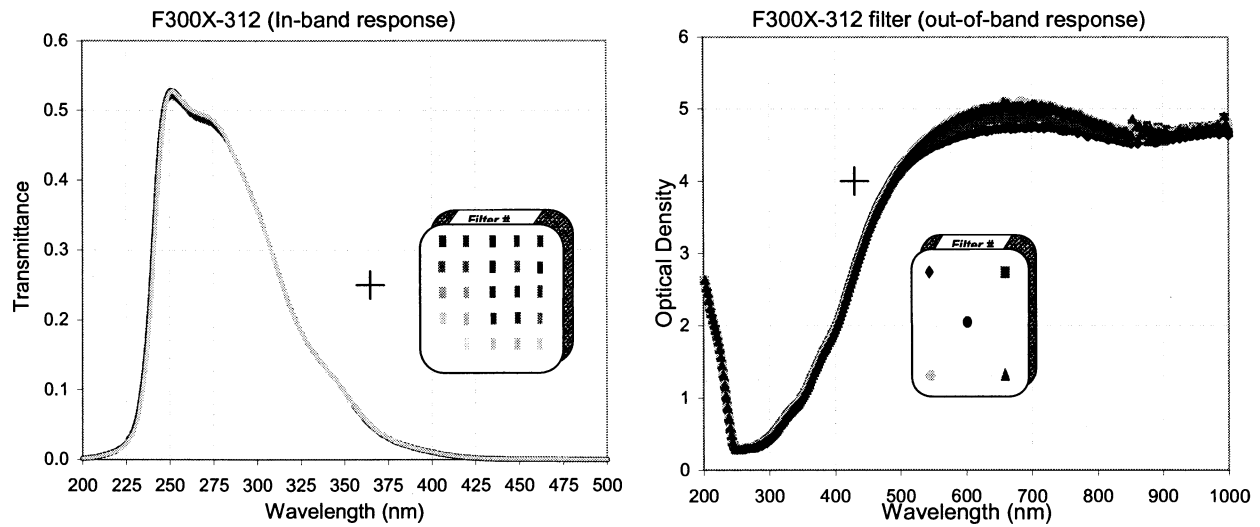


Figure 3. Wide band plot.

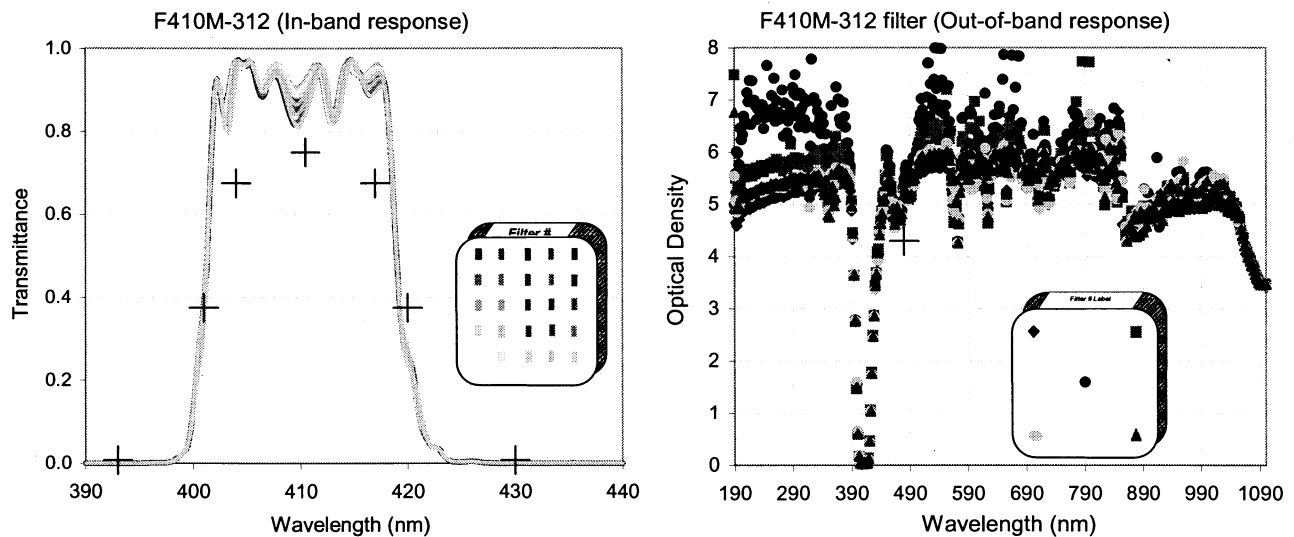


Figure 4. Medium band plot.

5. RESULTS AND DISCUSSION

5.1. Filter Spectral Performance

Figures 3-6 illustrates typical in and out of band scans for a few selected filters. These data are used to derive critical parameters, such as peak and average transmittance, central wavelength, band pass shape, depth of ripples, and out of band rejections. These parameter are then evaluated in light of the input specifications. A summary with these parameters for all the filters is shown in Table 1.

5.2. Transmitted Wavefront Error

This section describe the results of the data analysis that yield information such as the wavefront error (WFE), focus shift and wedge for each filters. Example phase retrieval data are shown in Fig ?? . The Zernike coefficients

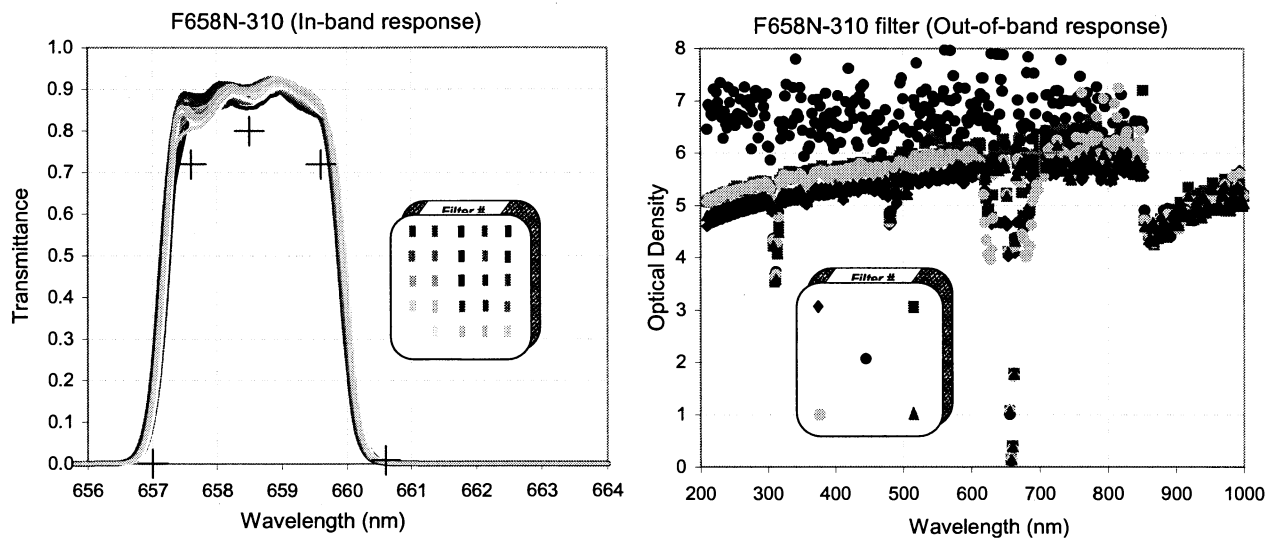


Figure 5. Narrow band plot.

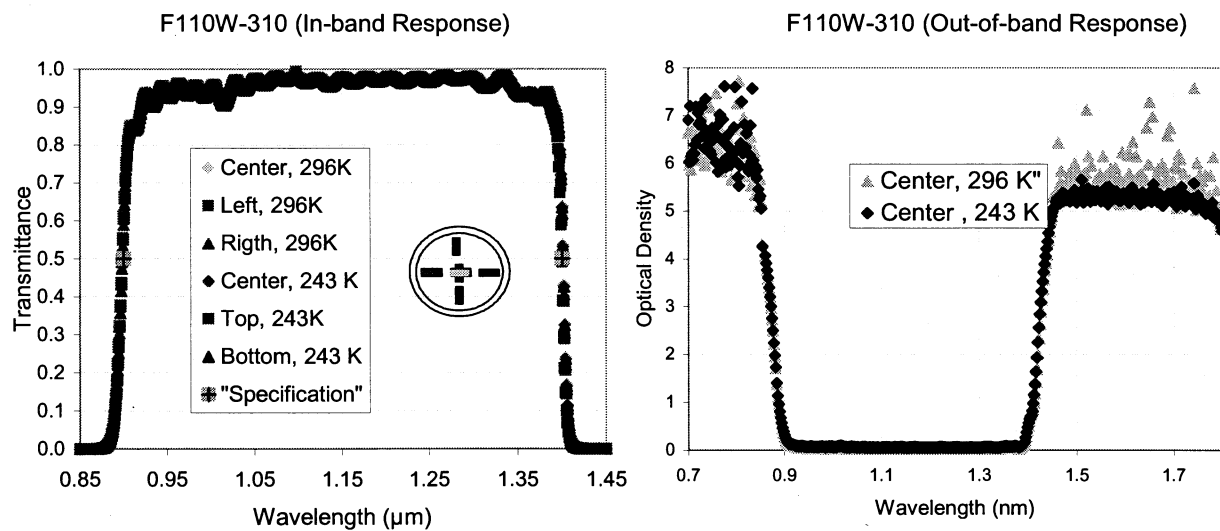


Figure 6. IR band plot.

Table 1. Summary of filter spectral performance.

Filter	Central λ (nm)	FWHM (nm)	Average Trans. In-Band 90% Pts.	90% Points (nm)		50% Points (nm)		Points @ T=1% (nm)		Optical Density (Out-of-Band)
				$\lambda_{\text{cut-on}}$	$\lambda_{\text{cut-off}}$	$\lambda_{\text{cut-on}}$	$\lambda_{\text{cut-off}}$	$\lambda_{\text{cut-on}}$	$\lambda_{\text{cut-off}}$	
F218W-311	216.8	33.9	16.21%	206.9	219.0	201.6	229.2	190.0	247.1	OD~4-7
F218W-312	217.8	40.2	19.99%	208.1	224.0	199.7	234.8	187.0	251.0	OD~4-7
F225W-303	224.4	48.5	20.95%	212.1	237.5	204.1	252.6	196.2	196.2	OD~5-6
F225W-305	227.9	54.7	30.50%	212.1	245.0	204.6	262.4	197.0	288.1	OD~4.5-5.5
F275W-310	266.4	39.9	27.94%	255.2	278.1	252.4	292.4	237.5	307.5	OD~4-6
F275W-312	266.7	41.3	29.24%	255.0	278.8	252.3	293.6	237.3	307.8	OD~4-6
F275W-316	273.0	46.3	44.44%	261.9	284.5	257.6	303.9	236.4	311.5	OD~3.5-5.5
F275W-317	263.7	48.1	43.06%	254.5	273.3	249.1	297.1	230.4	310.2	OD~4-6
F280N-310	279.5	4.3	26.06%	278.7	281.0	277.4	281.6	276.6	283.2	OD~4-6
F280N-311	276.7	4.6	25.32%	278.0	280.4	276.7	281.3	275.9	283.1	OD~4-6
F300X-311	264.5	71.7	47.66%	247.5	282.7	240.3	312.0	213.9	413.5	OD~4.5-5
F300X-312	263.8	75.3	49.46%	244.3	284.7	239.2	314.5	216.4	401.5	OD~4.5-5
F410M-311	410.9	18.3	92.85%	403.5	418.4	401.5	419.8	398.3	423.7	OD~5-7
F410M-312	410.6	17.8	91.97%	401.9	418.3	401.3	419.1	398.4	423.7	OD~5-7
F467M-311	467.9	21.8	88.48%	458.0	478.0	457.4	479.2	454.5	482.9	OD~4.5-7
F467M-313	467.6	21.9	89.57%	457.6	477.9	456.6	478.5	453.8	481.9	OD~4.5-7
F600LP-003	-	-	98.46%	622.3	-	608.4	-	593.0	-	OD~4.5-7
F606W-310	583.1	230.4	95.80%	480.8	707.1	479.0	709.5	469.9	720.8	OD~5-7
F606W-311	583.1	231.1	95.64%	480.7	707.5	478.7	709.5	469.4	721.2	OD~5-7
F621M-310	620.5	61.7	95.19%	592.1	650.3	590.6	652.3	581.7	661.5	OD~4.5-7
F621M-311	621.2	63.1	95.12%	593.5	650.2	590.4	653.5	494.9	661.7	OD~4.5-7
F656N-310	655.9	2.0	85.17%	655.1	656.7	654.9	657.0	654.4	657.3	OD~4.5-7
F656N-311	656.2	1.9	89.10%	655.5	657.0	655.2	657.2	654.7	657.7	OD~4.5-7
F658N-310	658.5	2.8	89.39%	657.3	659.7	657.1	659.9	656.7	660.4	OD~4.5-7
F658N-311	658.5	2.8	87.83%	657.2	659.6	657.0	659.9	656.6	660.3	OD~4.5-7
F689M-310	688.7	68.6	93.09%	657.0	721.9	655.0	723.6	646.1	731.7	OD~4.5-7
F689M-311	687.7	70.2	95.33%	655.7	721.3	652.9	723.1	642.2	731.5	OD~4.5-7

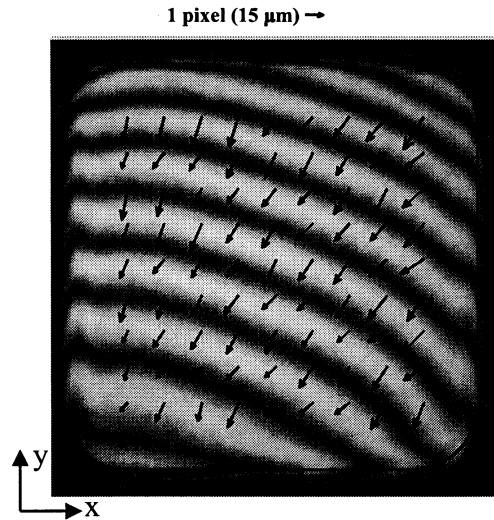


Figure 7. - Interferogram of F600LP-003. The interferometer was nulled without the filter. Superimposed are image displacement vectors as a function of position on the filter as measured by phase retrieval. As expected, the image displacement is perpendicular to the fringes. The correctness of the sign was verified by observing the fringe movement when pressing on the reference mirror.

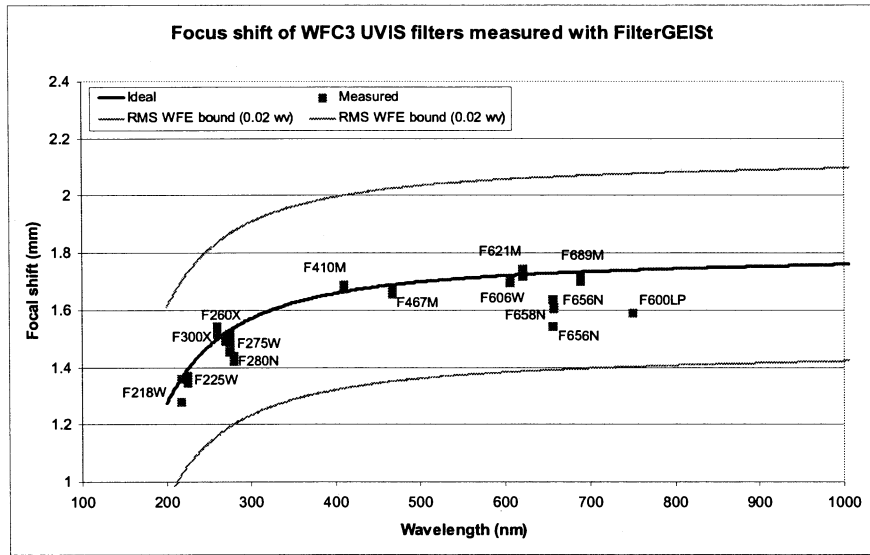


Figure 8. - Focus shift of flight candidate UVIS filters measured with phase retrieval data with FilterGEIST.

of the reference (no filter) data are subtracted from the filter data to give the net wavefront error due to the filter itself. The interpretation of the results is logically grouped in three categories:

1. The Zernike tilt terms describing the image displacement due to the filter, which is directly related to the wedge of the glass.
2. The Zernike focus term, to assess the parfocality of the filters in WFC3.
3. The remaining higher order terms that comprise what we consider at "the wavefront error".

The determination of the direction of the image displacement due to the wedge of the glass is important since in order to minimize the scatter among all filters in the WFC3 UVIS filter set, all filters are installed in the same wedge orientation. As interferometry was used on previous filters, we did comparisons of our measurements with an interferometric test. An example comparison, using one of the flight filters we tested, is shown in Fig 7. The filters have been constructed by design to have the proper thickness, given the wavelength of use and substrate index of refraction, to make the WFC3 filters parfocal. Note that the filters do not all have the same focus shift, since they are designed to be parfocal in the instrument, which requires compensating for the wavelength dependent shift of the two fused silica detector windows. Focus shift measurements for our tested filters are shown in Fig 8. For reference, curves are shown corresponding to 0.02 waves RMS wavefront error at 633 nm, which is the maximum allowable wavefront error for the filters.

5.3. Ghost Data Analysis

The specifications for WFC3 call for any ghost images to have less than 0.2% the intensity of the primary image. It was realized early on in the process of attempting to lamp. In order to predict the expected ghost performance of the filters in actual use, we performed monochromatic imaging with FilterGEIST for each filter from 200 to 1000 nm and, when possible, measured the relative ghost intensity. At some wavelengths, the ghost cannot be measured, usually because the throughput of the filters is (desirably) too low in some out-of-band regions to get sufficient signal. The data for the flight UV filters are plotted in Fig 9. The similarity of F218W-312, F225W-305, and F275W-317 is evident, all of which received the same anti-reflection coating. The AR coating of each filter was optimized in the design phase to minimize ghosting. eliminate ghost images that this would not in general be achievable for the UV filters, which was verified in the lab using broadband sources, including a 150W xenon arc lamp and a deuterium. After some interpolation and using model data to fill in the gaps, the relative ghost intensity can be multiplied by the filter throughput to yield an absolute ghost throughput, shown in Fig 10. To model predicted ghosting performance, we start with an input spectrum multiplied by the HST

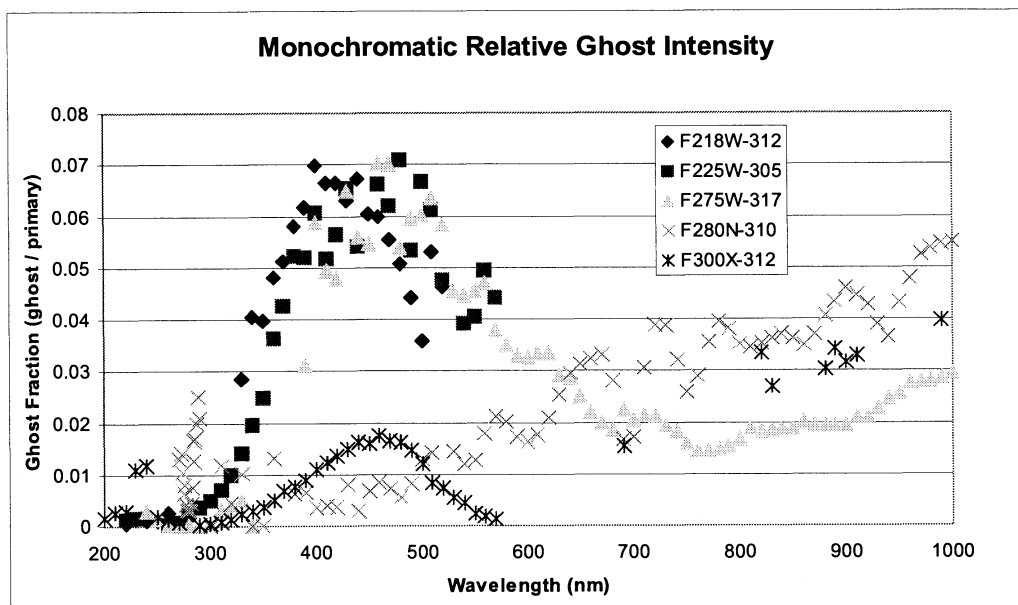


Figure 9. ghost data for flight UV replacement filters.

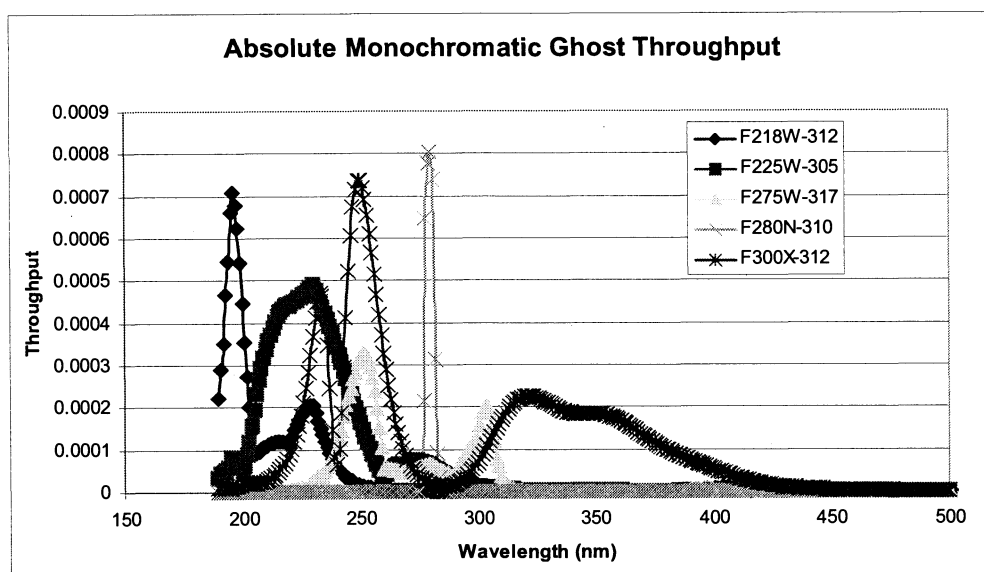


Figure 10. Absolute ghost throughput for UV filters. This is a product of measured filter throughput data and relative ghost intensity.

OTA and WFC3 throughput and detector sensitivity. The resulting spectrum can then be multiplied by both the ghost throughput and filter throughput, and then integrated to yield a total relative ghost intensity. We do this for standard stellar spectra with solar metallicity, using stellar types from L2 to O5, with the results plotted in Fig 11. The filters generally approach or exceed the specification for hot stars, but the ghosting increases for cooler stars when a significant fraction of the flux transmitted by the filter is out-of-band.

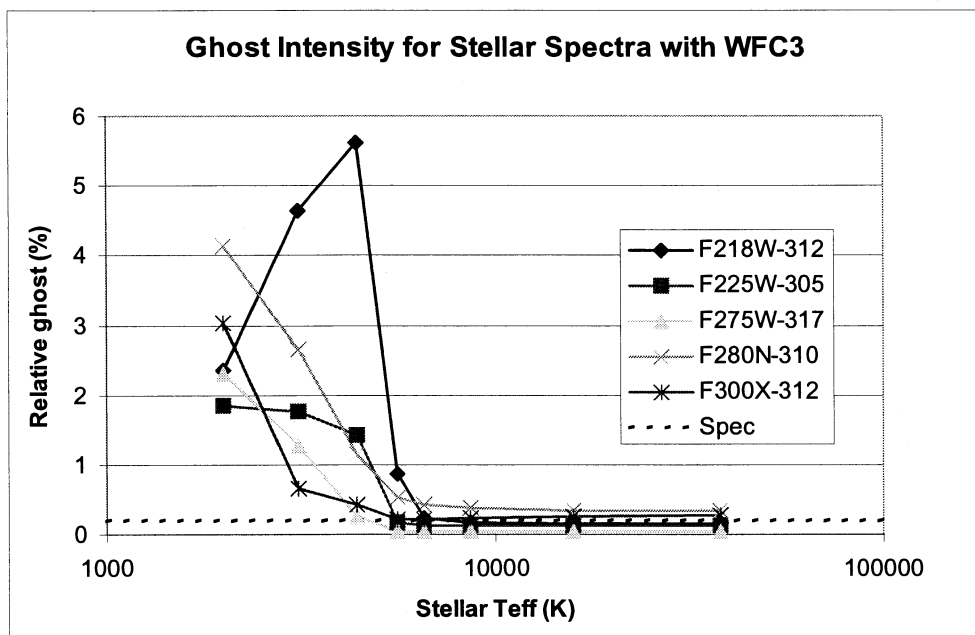


Figure 11. Predicted relative ghost intensity for UV filters when used with the WFC3 instrument.

Table 2. Results of transmitted wavefront error (WFE), focus shift, and image displacement due to filter wedge.

Filter	Central λ (nm)	RMS WFE (waves@633nm)		Focus Shift (mm)			Wedge Image Disp. (μm)
		Median	Max	Spec.	Measured	Diff.	
F218W-311	218	0.010	0.022	1.366	1.359	-0.007	2.25
F218W-312	218	0.013	0.033	1.366	1.277	-0.089	6.52
F225W-303	225	0.012	0.021	1.395	1.345	-0.050	2.87
F225W-305	225	0.012	0.025	1.395	1.368	-0.027	4.22
F260X-310	260	0.008	0.016	1.499	1.517	0.018	2.81
F260X-311	260	0.007	0.012	1.499	1.542	0.043	3.24
F275W-310	275	0.008	0.014	1.530	1.501	-0.028	4.21
F275W-312	275	0.007	0.011	1.530	1.486	-0.043	6.13
F275W-316	275	0.007	0.012	1.530	1.517	-0.013	5.65
F275W-317	275	0.009	0.017	1.530	1.452	-0.078	2.93
F280N-310	280	0.011	0.023	1.539	1.422	-0.117	3.88
F280N-311	280	0.009	0.022	1.539	1.440	-0.098	2.25
F300X-311	270	0.007	0.013	1.520	1.489	-0.031	4.01
F300X-312	270	0.015	0.030	1.520	1.500	-0.020	4.00
F410M-311	410	0.009	0.018	1.664	1.674	0.011	1.71
F410M-312	410	0.011	0.024	1.664	1.689	0.025	8.48
F467M-311	467	0.009	0.025	1.688	1.677	-0.010	5.46
F467M-313	467	0.012	0.023	1.688	1.653	-0.034	7.54
F600LP-003	750	0.013	0.028	1.739	1.589	-0.150	16.26
F606W-310	606	0.012	0.023	1.721	1.701	-0.020	2.93
F606W-311	606	0.007	0.014	1.721	1.694	-0.027	2.53
F621M-310	621	0.010	0.020	1.723	1.716	-0.007	6.21
F621M-311	621	0.007	0.014	1.723	1.741	0.017	2.90
F656N-310	656	0.009	0.026	1.728	1.540	-0.189	1.73
F656N-311	656	0.007	0.014	1.728	1.637	-0.091	2.64
F658N-310	658	0.007	0.022	1.729	1.607	-0.121	3.51
F658N-311	658	0.006	0.012	1.729	1.603	-0.126	1.05
F689M-310	689	0.010	0.018	1.733	1.699	-0.034	0.83
F689M-311	689	0.010	0.019	1.733	1.718	-0.015	1.77

6. CONCLUSIONS

In conclusion, we have verified that replacement filters for the WFC3 UVIS and IR channels instrument will meet science, minimum ghost, as well as environmental requirements to ensure durability of during testing, integration, and mission life of WFC3. The tests performed on these filters confirmed that they will meet spectral performance (both transmittance and out-of-band rejection) transmitted wave front error, focus shift, filter wedge, and physical dimensions.

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